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Procedia Engineering 10 (2011) 2003–2008

Engineering Procedia

ICM11

Constitutive behavior of injection molded short glass fiber reinforced thermoplastics: a phenomenological approach

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Abstract

SGFR thermoplastics exhibit a highly non-linear mechanical behavior under complex mechanical loadings, for various temperature and humidity conditions. A phenomenological constitutive model is proposed, describing several physical mechanisms such as viscoelasticity, thresholdless viscoplasticity and cyclic softening. The anisotropic microstructure resulting from the injection process is taken into account through orientation tensors.

Selection and peer-review under responsibility of ICM11

Keywords : Thermoplastics ; short fibers, injection molding, fiber orientation distribution, constitutive behaviour

1. Introduction

1.1. Industrial context and challenges

Aiming at reducing the CO_2 emissions, the automotive industry makes an increasing use of plastic materials in order to take advantage of their light weight and their complex mould designs. Polymer matrix composites (PMCs) and especially short glass fiber reinforced (SGFR) thermoplastics exhibit the required stiffness for structural applications (such as intake manifolds, inlet gas compressor exit, engine mount limiter). Moreover, the injection molding process of thermoplastic matrices with short fibers is compatible with high production rates and costly efficient. Automotive components located in the air income circuit are submitted to cyclic mechanical loadings (pulsed pressure) in variable environmental conditions (temperature, humidity). They thus have to be designed to exhibit a sufficient fatigue strength regarding fatigue, which explains the need for constitutive equations describing the cyclic behavior on a wide range of mechanical and environmental conditions.

Describing the cyclic behavior of SGFR thermoplastics is a complex task and raises many difficulties. First, the injection molding process results in an elaborate microstructure of the composite material. The

Selection and peer-review under responsibility of ICM11 doi:10.1016/j.proeng.2011.04.332

short glass fibers may not be homogeneously distributed in the polymeric matrix (clusters), their local orientations depend on the molding flow. Even if the industrial components are very often shell-like (2D) structures, the physical and mechanical properties of the thermoplastic composite vary across the spatial location, across the section thickness (heterogeneity), and depend on the spatial direction (anisotropy). From a mechanical point of view, the highly non-linear behavior of the polymeric matrix generates other kind of difficulties. To be representative of the actual service life of automotive components, cyclic loadings must involve creep-fatigue coupling and complex histories. Taking into account the fact that no fatigue criterion is generally accepted and used for SGFR thermoplastics, it means that many mechanical values have to be accurately predicted: strain and stress amplitudes, hystereses, cumulative irrecoverable strain, stiffness loss, etc. Last but not least, the temperature and also the humidity rate (in case of a polyamide matrix) greatly affect the mechanical properties of the thermoplastic composite. The industrial components for automotive applications undergo a large range of environmental conditions, which is the reason why the description of the cyclic behavior has to be valid under and beyond the glass transition temperature [1].

A phenomenological approach has been adopted in order to model the cyclic behavior of SGFR thermoplastics. As a matter of facts, the transition scale methods, even if promising and very present in the literature for such materials [2-4], are not suitable for numerical computations of industrial structures with highly non-linear behavior under cyclic loading histories. The topic of this paper is to present a way of modeling the anisotropic behavior resulting from the fiber orientation distribution in the framework of the non-linear constitutive equations proposed by the authors [5].

1.2. Numerical tools for the mechanical simulation

The overall numerical procedure leading to a reliable mechanical simulation involves different computations links. The first step is the injection molding simulation (with MoldFlow® for example), which results in the description of the fiber orientation distribution (FOD) in the structure. The complete FOD is not computed, but only its second and fourth order moments. The quantities are called orientation tensors, $\underline{\underline{a}}^{\psi}$ and $\mathbb{A}^{\psi}$. The fourth order orientation tensor $\mathbb{A}^{\psi}$ results from an interpolation based on the second order orientation tensor $\underline{\underline{a}}^{\psi}$, called closure equation.

In most cases, the meshes for the injection simulation and the mechanical simulation differ. An interpolation of the orientation tensors on the mechanical mesh is thus required, which can be achieved with a mapping software like Digimat®-MAP.

At last, the numerical integration of the constitutive equations in a FE software implies the development of a user-defined material subroutine, called UMAT in the case of Abaqus®. This subroutine may take as parameter at each Gauss point the orientation tensor previously computed, in order to account for the material anisotropy.

2. Constitutive equations for the cyclic behavior

2.1. Physical mechanisms and non-linear constitutive behavior

An extensive experimental campaign has been conducted on ISO527-2-1A tensile specimens, injected from the grade Zytel 70G35 HSLX (polyamide 66 with 35 wt% of short glass fibers) provided by DuPont de Nemours. The mechanical analysis highlighted several physical mechanisms: viscoelasticity at different timescales, viscoplasticity, non-linear kinematic hardening, and cyclic stiffness softening [1].

A constitutive behavior has been proposed by the authors [5]. The total strain is split into an elastic part, short and long term viscoelastic parts, and a viscoplastic part:

$$\underline{\underline{\varepsilon}} = \underline{\underline{\varepsilon}}_e + \underline{\underline{\varepsilon}}_{v1} + \underline{\underline{\varepsilon}}_{v2} + \underline{\underline{\varepsilon}}_{vp} \quad (1)$$

The stress is directly linked to the elastic strain through a fourth-order elastic stiffness tensor:

$$\underline{\underline{\sigma}} = \mathbb{C}^e : \underline{\underline{\varepsilon}}_e \tag{2}$$

The viscoplastic equivalent stress involves the hardening backstress $\underline{\underline{X}}$:

$$\mathcal{J}_{vp} = \sqrt{\left(\underline{\underline{\sigma}} - \underline{\underline{X}}\right) : \mathbb{P} : \left(\underline{\underline{\sigma}} - \underline{\underline{X}}\right)} \tag{3}$$

where $\mathbb{P}$ is a fourth order tensor similar to the Hill'48 [6] formulation. In the isotropic case, $\mathbb{C}^e$ only involves two material parameters (e.g. E and ν), and $\mathbb{P}$ equals $1.5\mathbb{K}$, implying J_{vp} being the von Mises equivalent stress. Note that the classical decomposition $\mathbb{I} = \mathbb{J} + \mathbb{K}$ of the fourth order identity tensor between spherical $\mathbb{J}$ and deviatoric $\mathbb{K}$ projectors is used. The viscoplastic strain rate depends on $\mathcal{J}_{vp}$ according to a thresholdless flow rule similar to [7]

$$\dot{\underline{\underline{\varepsilon}}}_{vp} = A\left[\sinh\left(\frac{\mathcal{J}_{vp}}{H}\right)\right]^m \frac{\mathbb{P}:\left(\underline{\underline{\sigma}} - \underline{\underline{X}}\right)}{\mathcal{J}_{vp}} = \lambda_{vp}\, \underline{\underline{n}}_{vp} \tag{4}$$

Eventually, the backstress evolution obeys an Armstrong-Frederick rule with parameters C and γ:

$$\dot{\underline{\underline{X}}} = \lambda_{vp}\left(\frac{2C}{3}\underline{\underline{n}}_{vp} - \gamma \underline{\underline{X}}\right) \tag{5}$$

Material parameters have been identified for different environmental conditions. Figure 1 illustrates the ability of the proposed model to represent the above-mentioned highly non-linear mechanisms.

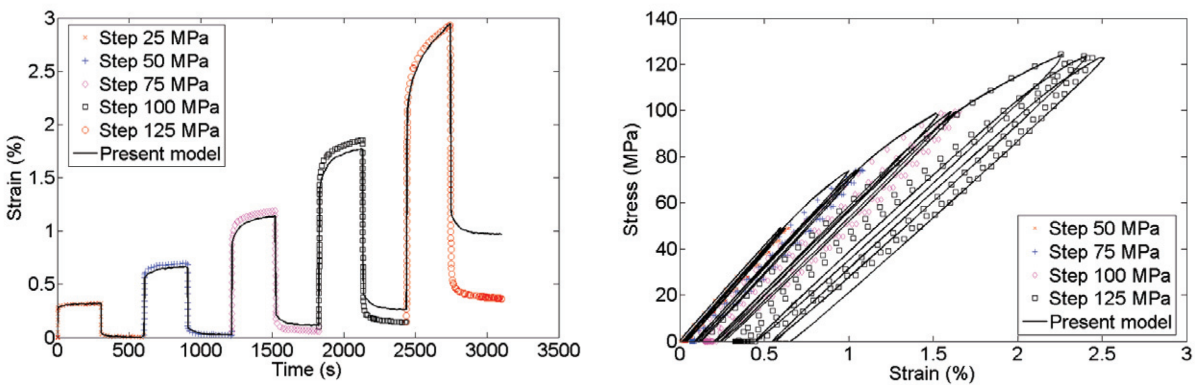

Fig. 1: Comparison between experimental data (symbols) and model prediction (continuous line) for different loading histories on ISO527-2-1A tensile specimen, at room temperature and RH=50%. Left: cyclic creep recovery test (stress controlled, 25 MPa/s), right: tension-tension tests with increasing steps (stress controlled, 2.5 MPa/s). These are *validation* results: the material parameters are previously determined, according to a specific identification strategy [5].

2.2. Taking into account the effect of the microstructure on elastic and viscoplastic properties

Material parameters have been identified on a specific microstructure, which can be considered as transversely isotropic. For another microstructure, it is necessary to propose a relationship between the orientation tensor and the mechanical properties.

The elastic tensor is built according to a two step homogenization. The elastic properties of a UD composite are computed thanks to a classical scheme for short fiber reinforced composites [8]. Based on Eshelby's results, the model of Mori-Tanaka [9] is appropriate when the volumic fraction of fibers does not exceed 30% (19.5% in our case). The elastic tensor results from an orientation averaging on stiffness tensors, which consists in the Voigt upper bound [10, 11]:

$$\mathbb{C}^e = \int_\Omega \psi(\underline{p})\mathbb{C}^{UD}(\underline{p})\,\mathrm{d}\underline{p} = \mathbb{C}^e\left(\mathbb{A}^\psi, \underline{\underline{a}}^\psi\right) \tag{6}$$

This expression can be written with the five elastic constants of Tandon and Weng [12], and with the use of the orientation tensors $\underline{\underline{a}}^{\psi}$ and $\mathbb{A}^{\psi}$, the latter being computed with the smooth orthotropic closure [13, 14].

The viscoelastic properties are assumed to be isotropic [15]. The viscoplastic equivalent stress $\mathcal{J}_{vp}$ depends on the orientation tensor, which reads $\mathbb{P} = \mathbb{P}(\mathbb{A}^{\psi})$. For example, one can suggest

$$\mathbb{P} = \frac{3}{2S}\mathbb{K} : \mathbb{C}^{e^{-1}} : \mathbb{K} \tag{7}$$

The physical meaning of such an equation is that viscoplastic mechanisms are easily activated in softer directions (e.g .with transversely oriented fibers). Moreover, $\mathbb{P}$ is orthotropic [6] if $\mathbb{C}^e$ is, and equals $1.5\mathbb{K}$ if $\mathbb{C}^e$ is isotropic, as requested. S is a normalization coefficient which ensures $\mathbb{P}_{1111} = 3/2$ for the ISO527-2-1A microstructure. This choice makes the identification of viscoplastic parameters easier with a 1D formulation.

3. Results on a notched fatigue specimen

Fatigue specimens (see Fig. 2, right) have been injection molded from the same polymer grade (PA66-GF35). As the orientation distribution around the circular notch is complex, these samples are used for the validation of the way we model the influence of the microstructure on the non-linear behavior.

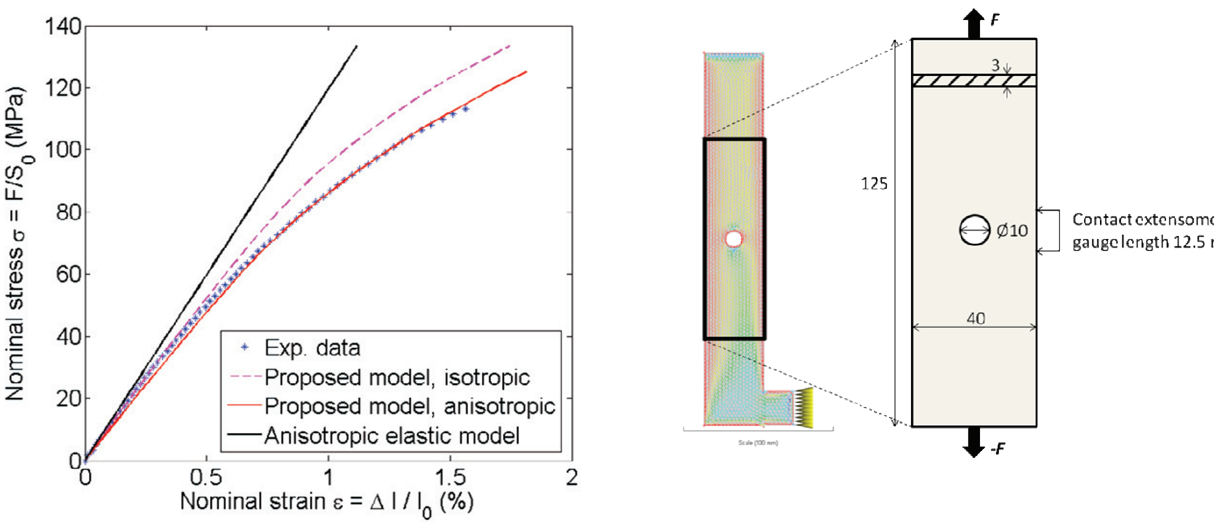

Fig. 2: Left, comparison between the experimental average strain measured by contact extensometer on a notched fatigue specimen subjected to a monotonic tension test ($\dot{F}$ = 100 N/s) and the predictions of the proposed model with or without taking into account the effect of the microstructure on $\mathbb{C}^e$ and $\mathbb{P}$, and of an anisotropic elastic model. Right, result of the injection molding simulation (MoldFlow®) of the notched fatigue specimen (K_t = 2.5), and scheme of the experimental set. The load F is applied by means of two hydraulic grips.

In Figure 2 we show that a linear elastic behavior $\underline{\underline{\sigma}} = \mathbb{C}^e : \underline{\underline{\varepsilon}}_e$, with an anisotropic stiffness tensor, cannot be used to predict the mechanical behavior, even on monotonic tension at small stresses. Non-linear mechanisms are indeed easily activated because of the stress concentration. On the other hand, the proposed model without taking into account the microstructure cannot be sufficient either because viscoplastic mechanisms are highly dependent on the microstructure. Note that the initial stiffness is correct because the fibers are mainly oriented in the loading direction. The proposed model with anisotropic $\mathbb{C}^e$ and $\mathbb{P}$ computed with Eq. (7) leads to a fairly good fit between experimental and numerical data.

The same conclusions can be drawn from the observation of the strain fields (in the loading direction, see Fig. 3). However, even if better than with the anisotropic elastic or the isotropic non-linear models, the correlation field with the proposed anisotropic model is not totally satisfying. The strain hot spots are not well located. Microstructural observations (e.g. with X-ray micro-tomography) must be performed to assess if the error comes from a bad simulation of the FOD, or if the proposed model should be improved.

Besides, as the model is developed for the description of the cyclic behavior for fatigue design, it will be necessary to achieve the same comparative study for cyclic loadings.

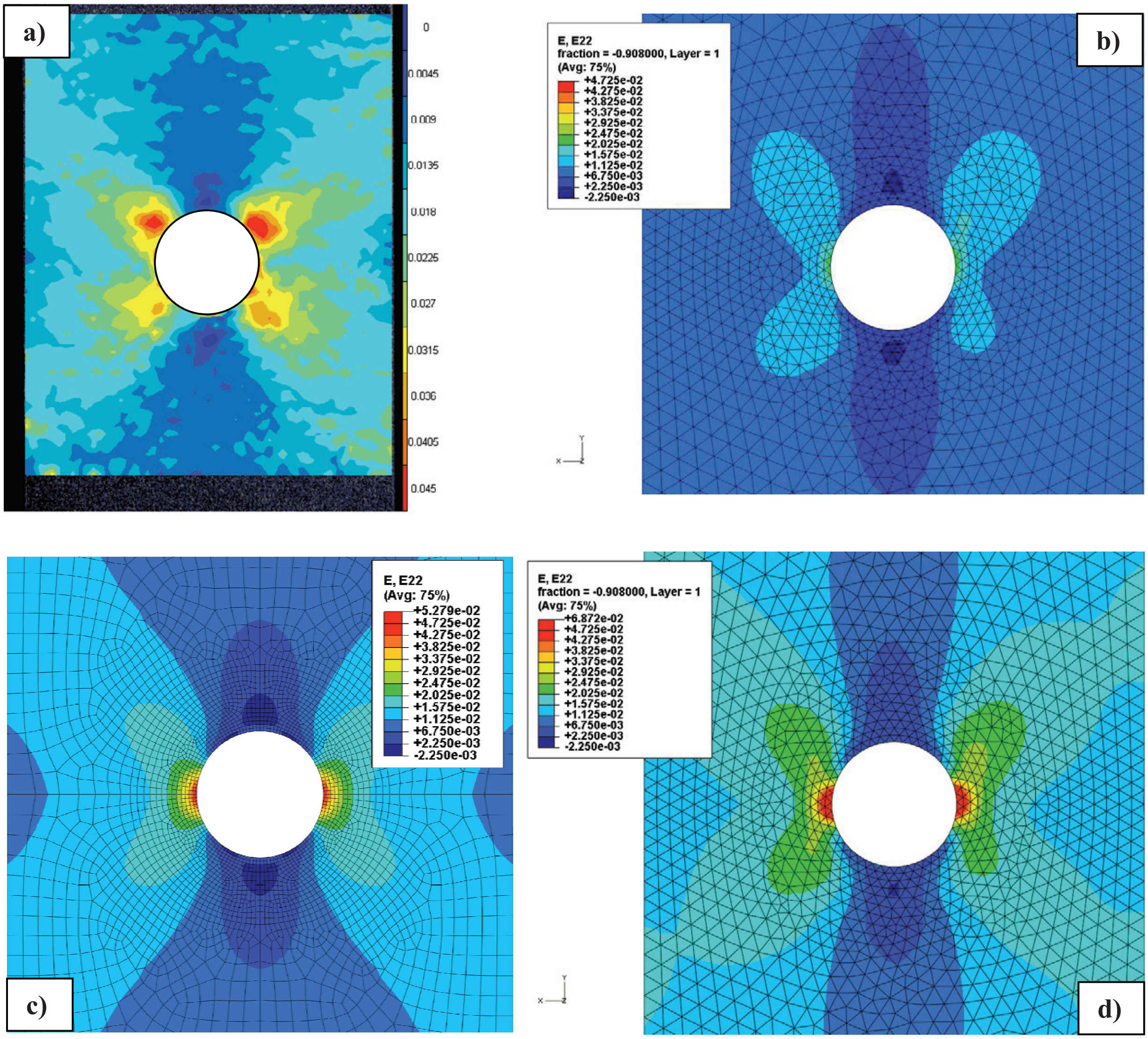

Fig. 3: Comparison between the strain fields ε_{22} measured by Digital Image Correlation (a) and resulting from the numerical simulation with an anisotropic elastic model (b), or with the proposed model with (d) or without (c) taking into account the influence of the fiber orientation distribution on $\mathbb{C}^e$ and $\mathbb{P}$. The nominal stress equals 106 MPa in direction $\underline{e}_2$ and the colour scales are the same on all four pictures.

4. Discussion and conclusions

The proposed phenomenological constitutive model fairly describes the non-linear mechanisms occurring during cyclic loadings under various environmental conditions. Whereas scale transition methods naturally take account for material anisotropy in the equivalent material behavior, it is here necessary to develop specific phenomenological relationships such as Eqs. (6) and (7).

Nevertheless, several improvements could be brought to the current model. The choice of the closure equation has an impact on the elastic mechanical properties and must be discussed [11]. Regarding the viscoplastic flow rule, an anisotropic equivalent stress has been proposed, but the hardening parameters C and γ could also be replaced by anisotropic tensors. At last, micro-tomographic observations are required in order to quantify the accuracy of injection simulation and the prediction of orientation tensors.

This study must thus be completed by an experimental campaign focused on the influence of the microstructure on the mechanical response. Samples milled out at different angles from end line gated plates are currently tested in order to assess or to improve the hypotheses of the present approach.

Acknowledgements

This work was supported by PSA Peugeot-Citroën. The authors gratefully acknowledge DuPont de Nemours for providing specimens and material data.

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